Contribution of Each Motor Point of Quadriceps Femoris to Knee Extension Torque During Neuromuscular Electrical Stimulation

Derrick Lim, Mikael Del Castillo, Austin J. Bergquist, Matija Milosevic, and Kei Masani

***Abstract*— Transcutaneous neuromuscular electrical stimulation (NMES) can be used to activate the quadriceps femoris muscle to produce knee extension torque via seven distinct motor points, defined as the most sensitive locations on the muscle belly to electrical stimuli. However, it remains unclear how much individual motor points of the quadriceps femoris muscle contribute to the knee joint torque. Here we systematically investigated the contribution of each motor point of the quadriceps femoris muscle to the knee joint torque produced by paired electrical stimuli. Ten able-bodied individuals participated in this study. Paired electrical stimuli was applied by delivering electrical impulses on the motor points in all combinations among seven motor points (i.e., totaling to 127 combinations) at two different stimulation intensities (i.e., 25% and 50% of the maximum) while recording isometric knee joint torque. The contribution of individual motor points was estimated using statistical analyses. We found that a linear addition of twitch torques induced by single motor point stimulus overestimated the twitch torques induced by multiple motor point stimulations, suggesting overlaps in muscle fibres activated by each motor point. Using multiple linear regressions, we identified the average contribution of each motor point to the knee extension torque during paired electrical stimuli and found significant differences between these torque contributions. We demonstrated that seven distinct motor points can be activated for the quadriceps muscle group using paired electrical stimuli and identified the contribution of each motor point to knee extension torque during twitch muscle contraction; these findings provide useful information to design rehabilitation using NMES on quadriceps femoris muscles.**

Manuscript received July 9, 2020; revised November 9, 2020; accepted December 6, 2020. Date of publication January 19, 2021; date of current version March 2, 2021. The work of Austin J. Bergquist was supported in part by the Spinal Cord Injury Ontario Post-Doctoral Fellowship and in part by the Canadian Institutes of Health Research Fellowship under Grant 0040678. The work of Kei Masani was supported by the Canadian Institutes of Health Research under Grant PJT148851. *(Corresponding author: Kei Masani.)*

Derrick Lim and Kei Masani are with the KITE Institute-University Health Network, Toronto, ON M4G 3V9, Canada, and also with the Institute of Biomedical Engineering, University of Toronto, Toronto, ON M5S 3G9, Canada (e-mail: k.masani@utoronto.ca).

Mikael Del Castillo is with the Graduate School of Engineering Science, Department of Mechanical Science and Bioengineering, Osaka University, Toyonaka 560-8531, Japan.

Austin J. Bergquist is with the KITE Institute-University Health Network, Toronto, ON M4G 3V9, Canada.

Matija Milosevic is with the Department of Mechanical Science and Bioengineering, Graduate School of Engineering Science, Osaka University, Toyonaka 560-8531, Japan.

This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2021.3052853, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2021.3052853

***Index Terms*— Electrical stimulation, knee, motor point, torque, quadriceps.**

I. Introduction

TRANSCUTANEOUS neuromuscular electrical stimulation (NMES) has been used to artificially activate the muscles by applying short electric impulses on the surface of the skin. NMES has been utilized for in many applications including strength training in able-bodied individuals and athletes [1] as well as neurorehabilitation for individuals with neurological impairments [2]. When NMES is used to generate functional movements by temporally sequencing muscle contractions, it is called functional electrical stimulation (FES) [3], [4]. FES has successfully been utilized in numerous therapeutic and orthotic applications such as restoration of upper limb voluntary control [5] and walking [6]. NMES of the quadriceps femoris muscle group has most successfully been applied in clinical practice for rehabilitation in the form of FES [7], [8]. For example, NMES of the quadriceps femoris was used in FES cycling in individuals with spinal cord injury, which was shown to be advantageous for increasing muscle strength [7], [9] as well as improving bone mineral density [10], aerobic fitness, and cardiovascular health [11].

NMES can be applied either over the muscle belly or on the nerve trunk running superficially. In clinical settings, NMES is achieved either by electrically stimulating a group of muscles with a pair of large electrodes to cover the entire muscle group or using anatomical charts to map the approximate locations of motor points to guide electrode placement. For instance, a pair of large electrodes located at the proximal and distal ends of the thigh is often used for activating the quadriceps femoris. However, this configuration is less effective for inducing joint torques, and proper identification of motor points is recommended [12], [13]. The motor point is a location over the muscle belly that is most responsive to electrical stimuli. The motor points are identified manually using a probe electrode to search the location that causes largest identifiable muscle twitch to the delivered electrical impulses [13]–[15]. In case of the quadriceps femoris, a total of seven different motor points can be identified: three motor points for the vastus lateralis (VL), two motor points for the rectus femoris (RF), and two for the vastus medialis (VM) [14]. Positioning the electrodes optimally over the seven motor points of quadriceps femoris is essential to maximizing the stimulation-induced knee extension torque outputs.

TABLE I
PARTICIPANT AGE AS WELL AS STIMULATION AMPLITUDE (mA) AND CORRESPONDING KNEE EXTENSION TORQUE (Nm) EXERTED AT FES_{25}, FES_{50}, AND FES_{MAX}

Participant	**Age** *(year)*	**Sex** *(M/F)*	**FES_{max}** *(mA)*	**FES_{25}** *(mA)*	**FES_{50}** *(mA)*	**FES_{max}** *(Nm)*	**FES_{25}** *(Nm)*	*(%MVC)*	**FES_{50}** *(Nm)*	*(%MVC)*	**MVC** *(Nm)*
P1	33	M	110	30	50	70.3	19.9	10.3	36.2	18.8	193
P2	25	M	100	40	70	74.3	27.9	10.1	52.4	19.0	276
P3	21	M	110	30	50	64.5	19.6	20.5	32.3	33.8	96
P4	22	M	110	20	50	106.0	21.0	6.0	49.2	14.1	349
P5	49	M	110	30	60	80.2	26.0	13.8	48.7	25.8	189
P6	18	F	70	20	50	36.4	8.9	6.9	17.8	13.7	130
P7	19	M	70	10	40	62.9	8.6	6.0	26.2	18.5	142
P8	27	F	120	20	50	35.7	7.4	10.9	16.9	24.9	68
P9	28	F	120	30	40	60.4	15.4	13.5	24.8	21.8	114
P10	20	M	110	20	40	83.5	18.8	11.3	34.7	20.8	167
Avg	26.2	-	103.0	25.0	50.0	67.42	17.35	10.93	33.92	21.12	173.4
SD	9.3	-	18.3	8.5	9.4	21.11	7.19	4.38	12.88	5.95	85.3

To date, little consideration has been given to optimization of electrode placement on the quadriceps to maximize the efficiency in torque generation during therapies using NMES, which is beneficial in training muscles in general to improve muscle functions. Specifically, it remains unknown how stimulation of different motor points in the quadriceps muscle group contributes to torque output and how stimulating different combinations of motor points can affect the output. Each motor point stimulus most likely activates a portion of muscle fibres within a muscle, while also having some overlapping fibres with those activated by other adjacent motor points. The activated muscle fibres contribute to knee extension torque with a degree. If the overlap is minimum, the sum of each motor point contribution would give the exerted knee extension torque. Therefore, the purpose of this study was to systematically investigate the contribution of each motor point of quadriceps femoris muscles to the knee joint torque produced by paired electrical stimuli, which is an essential element of NMES.

II. METHODS

A. Participants

Ten able-bodied individuals participated in this study (age: 18-49 years; 7 males, 3 females) (Table I). No participants had a history of neurological impairments or musculoskeletal injury. As the participants were recruited among the laboratory members, all participants were familiar with electrical stimulation. All participants gave written informed consent in accordance with the principles of the Declaration of Helsinki. The study protocol was approved by the local institutional ethics committee.

B. Electrical Stimulation Protocol

Paired electrical stimuli was delivered using seven constant current electrical stimulator units (Compex II, Compex Motion, Switzerland) as shown in Fig. 1. For each participant, the seven motor points on quadriceps femoris were first identified for the right leg using a stimulating pen electrode while subjects were seated with the knee flexed at 90° and remained relaxed, as outlined by Botter *et al.* [14] and Sung *et al.* [16] (Fig. 2a). Specifically, the experimenter identified the motor points by moving the stimulating pen electrode across each muscle and marking the points where the response was largest on the: 1) vastus lateralis proximally (VL_p), 2), centrally (VL_c), and 3) distally (VL_d); 4) rectus femoris proximally (RF_p) and 5) distally (RF_d); as well as 6) vastus medialis proximally (VM_p) and 7) distally (VM_d).

Active electrodes (5 cm × 5 cm) were then positioned on each of the seven identified motor points. They were stimulated by applying doublet stimulations, i.e., consisting of two monophasic rectangular pulses with a 10 ms inter-pulse interval (i.e., doublets), each of 300 μs pulse duration (Fig. 2a). Two ground electrodes (5 cm × 10 cm) were positioned on the proximal end of the front part of the thigh side-by-side (Fig. 2a). The seven different motor points were activated in all possible combinations (see below), using the seven stimulator units that were synchronized using a push-button switch controlled by the experimenter. The maximum tolerable stimulation current amplitude (FES_{max}) was determined for each participant by sending impulses (i.e., doublets) to all seven motor points simultaneously, ranging from 10 mA up to 120 mA in 10 mA increments. FES_{max} was decided as the stimulation current amplitude that the participant could endure without significant discomfort or pain. The stimulator's maximum output current is 120 mA. Five participants (i.e., P1, P3-P5, and P10) almost reached the stimulator's maximum output current with an FES_{max} of 110 mA and two participants (i.e., P8 and P9 in Table I) tolerated the maximum output current of 120 mA, as such this might not be their true maximum tolerable current (FES_{max}) considering the technical limitation. The torque generated by each stimulus was recorded and the stimulation amplitudes were chosen as the current (rounded to the nearest 10 mA) that generated: 1) 25% (FES_{25}) and 2) 50% (FES_{50}) of the torque output at FES_{max}. The same stimulation current amplitude was also used for each of the seven motor point locations for that participant. Considering the large number of stimulation that each participant experienced (i.e., 260 doublet stimulations), we decided to use twitch contraction instead of tetanic contraction, and to use the doublet stimulation to increase the torque generation instead of single stimulation. The choice of the two target levels was made because FES_{50} was found to be sufficiently large and comfortably acceptable for anybody in our preliminary study, and FES_{25} was selected as a weaker stimulation intensity that

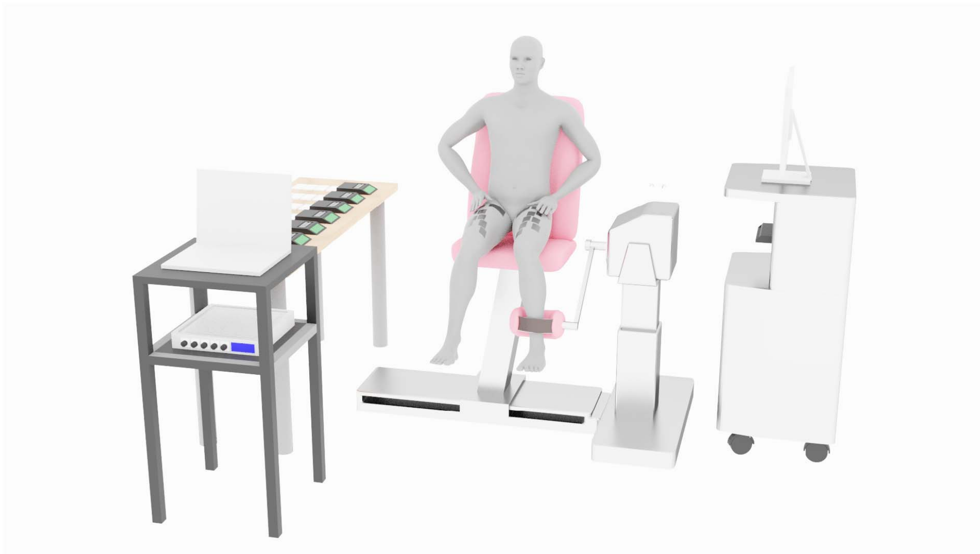

Fig. 1. Experiment setup with (left) seven Compex stimulators and (right) Biodex dynamometer for measuring twitch torque response.

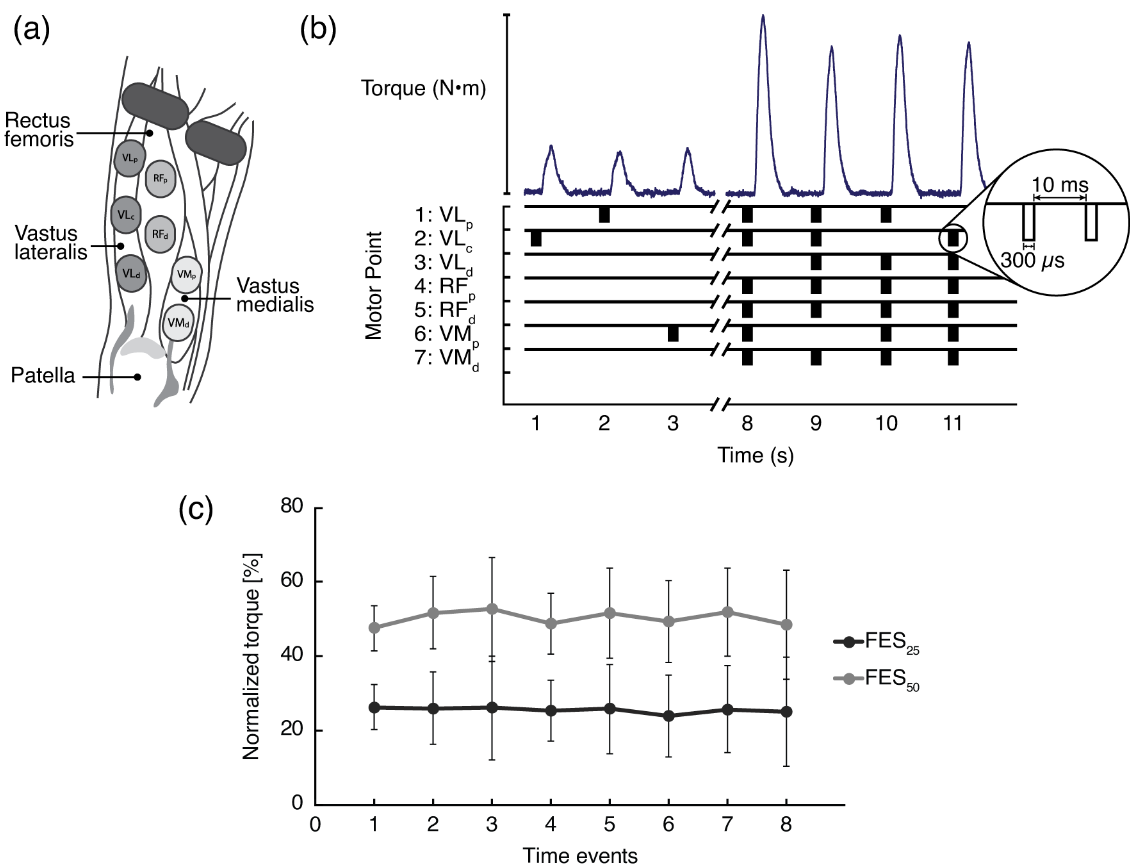

Fig. 2. (a) Illustration of motor point locations that were stimulated (black): vastus lateralis proximally (VL_p), centrally (VL_c), and distally (VL_d); rectus femoris proximally (RF_p) and distally (RF_d); as well as vastus medialis proximally (VM_p) and distally (VM_d); and two ground electrodes (gray) were positioned proximally on the nerve endings across quadriceps muscles; (b) Sample torque outputs produced by single motor points and different combinations of 6 motor points chosen from 7 possible locations, which were stimulated using doublets impulses every 1 s; and (c) The normalized torque outputs for FES_{25} (black) and FES_{50} (gray) conditions in the group averages with standard deviations.

is considerably different from the larger target (i.e., FES_{50}) and resting.

During the experiment, at each stimulation current amplitude, a total of 127 different combinations of motor point stimulations were tested: 7 combinations for 1 motor point, 21 combinations for 2 motor points, 35 combinations for 3 motor point, 35 combinations for 4 motor points, 21 combinations for 5 motor points, 7 combinations for 6 motor points, and 1 combination for 7 motor points ($nCr = \frac{n!}{r!(n-r)!}$, where n = 7 and r = 1, 2, 3, 4, 5, 6, 7). Each stimulation combination was delivered every 1 s (Fig. 2b). The stimulation combinations with the same number of motor points were delivered as blocks, while the order in which these blocks were delivered was randomized between participants. Each stimulation combination was delivered twice by reversing the order of the blocks. The responses of the two trials were averaged. Only the stimulation of all 7 motor points was repeated 8 times during the data collection to determine muscle fatigue. These trials were spread out across the duration of both trials, placed between every 2 stimulation blocks. A break of at least 5 min was given between different stimulating amplitudes.

C. Torque Measurements

During the experiment, participants were seated in a height adjustable chair with their arms on their chest and straps over the hips to stabilize the pelvis and the trunk. Biodex Dynamometer (Biodex 3, Biodex Medical Inc, USA) was used to measure right knee extensor torque in the isometric condition (Fig. 1). The hip and knee joints were positioned such that they were flexed at 90° and the calf was secured to the dynamometer arm using a strap above the malleoli. Dynamometer axis of rotation was aligned with the flexion/extension of the knee joint, with the resistance pad fixed at the distal end of the thigh. The analog output was sampled at a 1,000 Hz sampling frequency using a data acquisition system (Powerlab 16/35, AD Instruments, Australia) and stored on a computer for post processing. The knee extension torque during the maximum voluntary contraction (MVC) were recorded twice with sufficient break in-between before the abovementioned stimulation protocol, and the larger torque was determined as the MVC torque.

D. Data Analyses

The stored torque outputs were analyzed using custom programs (MATLAB R2020, MathWorks, Inc., USA). Prior to all statistical analyses, we used Shapiro-Wilk test to check whether the data were normally distributed. Whenever we found that the normality was breached, we applied non-parametric tests. All statistical tests were performed using MATLAB (R2020, MathWorks, Inc., USA). Significance level was set to $p < 0.05$.

The peak torque was identified and normalized as a percentage of the exerted torque at FES_{max}. Then the normalized peak torque at each stimulation combination was determined by averaging the two peak torque values for each participant. For the stimulation combination with all 7 motor points that we collected 8 times, the average of eight peak torques was calculated for each participant. The peak torque with all 7 motor points was also used to assess the muscle fatigue. That is, the peak torque with all 7 motor points at each time event was group-averaged, and the group mean values were compared between the time events for each stimulation intensity using a Kruskal-Wallis test.

The contributions of each motor point to the total generated torque output was estimated using two methods for each stimulation intensity as follows. In the first method, the peak torque obtained when each motor point was individually stimulated (T_{VL_p}, T_{VL_c}, T_{VL_d}, T_{RF_p}, T_{RF_d}, T_{VM_p}, T_{VM_d}) was identified and normalized to the maximum twitch torque exerted by the stimulation of all seven motor points. This normalized peak torque from each motor point as the contribution of each motor point was compared using a two-way repeated measures ANOVA test with the Holm-Bonferroni for post hoc analysis to examine the effect of motor point stimulation location and stimulation intensity on the torque output. However, this method probably overestimated the contribution of each motor point due to overlaps in muscle fibre regions activated by the motor point stimulation. The effect of the possible overlapping on overestimating torque contribution was evaluated by calculating the expected torque (T_E) for all possible combinations of motor point activations. T_E was computed by multiplying the activation matrix ($A_{i,j}$) with the torque output of each motor point (T_{VL_p}, T_{VL_c}, T_{VL_d}, T_{RF_p}, T_{RF_d}, T_{VM_p}, T_{VM_d}) and then summing the contributions from each motor point (i.e. the columns of the resultant matrix) for j = 1...127 combinations (Eqn. 1):

$$T_E = A_{i,j} \times T_{single\,motor\,point},$$

where

$$A_{i,j} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,7} \\ \vdots & \ddots & \vdots \\ a_{127,1} & \cdots & a_{127,7} \end{bmatrix}$$

with $a_{i,j}$ corresponding to the indices, which were set to 1 if the motor point was stimulated and 0 if it was not stimulated. The columns (j = 1...7) of $A_{i,j}$ correspond to the activation index of each motor points and the rows (i = 1...127) correspond to the combinations. $T_{single\,motor\,point} = \begin{bmatrix} b_1 \\ \vdots \\ b_7 \end{bmatrix}$ is the vector containing the torques associated with each individual motor point stimulation such that b_1 is the torque output from stimulating the first motor point. Finally, for each participant and for each stimulation intensity, a linear regression analysis was applied between T_E and the measured torque output $T_M = \begin{bmatrix} c_1 \\ \vdots \\ c_{127} \end{bmatrix}$ using all 127 stimulation combinations. To extrapolate how closely the T_E predicted the measured torque, one sample t-tests were used to compare the slopes and y-intercepts of the linear regression fits to 1 and 0, respectively. The effect of overlap are likely to be large especially when motor points within the same muscle head were stimulated, while it may be small when only the motor points from different muscle heads were stimulated. Therefore, to further assess the effect of overlap, we isolated a subset of the full data consisting only of stimulation combinations with one motor point from each muscle head (i.e., in total 35 combinations), and applied the same linear regression analysis.

In the second method, we estimated the contribution of each motor point to the overall torque output using a multiple linear regression analysis for each participant and for each stimulation intensity. $T_M = \begin{bmatrix} c_1 \\ \vdots \\ c_{127} \end{bmatrix}$ represented the measured

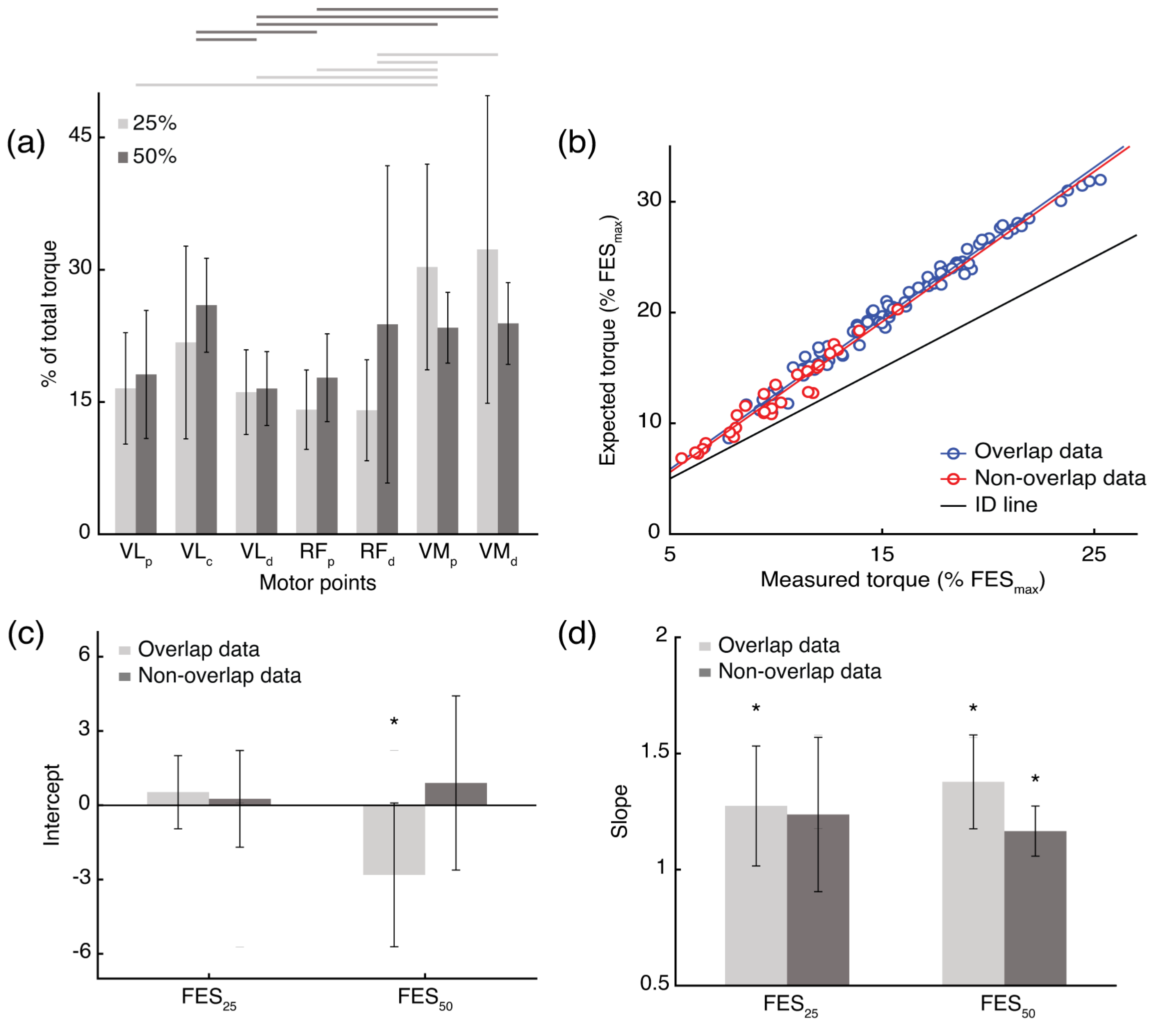

Fig. 3. (a) Summary of percent torque contribution of each motor point as calculated by normalizing the torques associated with each individual motor point stimulation to the maximum twitch torque exerted by the stimulation of all seven motor points: vastus lateralis proximally (VL_p), centrally (VL_c), and distally (VL_d); rectus femoris proximally (RF_p) and distally (RF_d); as well as vastus medialis proximally (VM_p) and distally (VM_d) at the stimulating amplitudes that produced: 25% (FES_{25}) and 50% (FES_{50}) torque of that at the maximum stimulus intensity (FES_{max}). Illustrated are the mean (SD) contributions across all participants with significance differences calculated using the Holm-Bonferroni method; (b) expected torque (T_E) against measured torque (T_M) and its linear regression at FES_{25} for both the full data as well as the nonoverlapping subset of the data for a participant. Torque data are normalized as a percentage of when all seven motor points were stimulated simultaneously at FES_{max}; (c) y-intercept and (d) slope of the linear regressions of T_E against T_M for both full data and subset. Significance from the t-test results were set to $p < 0.05$.

peak torque values for all 127 stimulation combinations. In the multiple linear regression analysis, T_M was defined as the dependent variable, while the independent variables were defined as seven column vectors ($A_{i,1}$, $A_{i,2}$, $A_{i,3}$, $A_{i,4}$, $A_{i,5}$, $A_{i,6}$, $A_{i,7}$) of the activation matrix ($A_{i,j}$), which correspond to when each motor point was active/inactive:

$$T_M = d_1 \begin{bmatrix} a_{1,1} \\ \vdots \\ a_{127,1} \end{bmatrix} + d_2 \begin{bmatrix} a_{1,2} \\ \vdots \\ a_{127,2} \end{bmatrix} + d_3 \begin{bmatrix} a_{1,3} \\ \vdots \\ a_{127,3} \end{bmatrix} + d_4 \begin{bmatrix} a_{1,4} \\ \vdots \\ a_{127,4} \end{bmatrix} + d_5 \begin{bmatrix} a_{1,5} \\ \vdots \\ a_{127,5} \end{bmatrix} + d_6 \begin{bmatrix} a_{1,6} \\ \vdots \\ a_{127,6} \end{bmatrix} + d_7 \begin{bmatrix} a_{1,7} \\ \vdots \\ a_{127,7} \end{bmatrix}$$

where $D = \begin{bmatrix} d_1, & \ldots, & d_7 \end{bmatrix}$ represented the contribution of each motor point. The multiple linear regression identified the matrix D. The identified contribution of each motor point was then compared using a two-way repeated measures ANOVA test with the Holm-Bonferroni for post hoc to examine the effect of motor point stimulation location and stimulation intensity on the torque output.

III. Results

A. Fatigue Analyses

The stimulation current amplitude and the exerted knee extension torque for each participant are summarized in Table I. Results of the fatigue analysis are presented in Fig. 2c which shows slight fluctuations across the time events. The Kruskal-Wallis tests however showed no significant differences (P = 0.999 and P = 0.998 for FES_{25} and FES_{50}, respectively) between the torque outputs at the time events, suggesting that the fatigue effect does not need to be considered for subsequent analyses.

B. First Method for Estimation of Contributions Using a Single Motor Point

Fig. 3a presents the group average torque contribution of each motor point as a fraction of the torques associated with each individual motor point over the maximum twitch torque exerted by the stimulation of all seven motor points for both FES_{25} and FES_{50} stimulation intensities across all participants. A two-way ANOVA revealed a significant main effect of the motor points ($P < 0.001$). No significant main effect of the stimulation intensity was found ($P = 0.691$). A significant interaction effect was found between motor point and stimulation intensity ($P = 0.028$). The post-hoc analysis showed little to no significant differences between torque contributions from motor points on the same muscle head. Significant differences were mainly found between motor points on the VM and those on the VL and RF (Fig. 3a).

Linear regression for T_E and T_M was repeated for each participant and at both stimulation intensities. Fig. 3b shows an example scatter plot of T_E against T_M and its linear regression at FES_{25} for both the full data as well as the subset data. A clear linear fit is shown; for the full data, the coefficient of determination was quite high with the group median of 0.92 (ranging from 0.99 to 0.77) for FES_{25} and the group median of 0.92 (ranging from 0.95 to 0.55) for FES_{50}. At FES_{25}, the linear regression fits have the group median slope of 1.20 (ranging from 0.923 to 1.68), and the group median y-intercept of 0.689 (ranging from −3.08 to 2.18). At FES_{50}, the regression fits have a group median slope of 1.29 (ranging from 1.07 to 1.71) and a group median y-intercept of −2.30 (ranging from −7.35 to 1.19). For the subset data, the coefficient of determination was slightly lower with the group median of 0.80 (ranging from 0.97 to 0.68) for FES_{25} and the group median of 0.83 (ranging from 0.86 to 0.12) for FES_{50}. At FES_{25}, the linear regression fits have the group median slope of 1.18 (ranging from 0.808 to 1.90), and the group median y-intercept of −0.0705 (ranging from −2.27 to 4.06). At FES_{50}, the regression fits have a group median slope of 1.14 (ranging from 1.05 to 1.40) and a group median y-intercept of 0.796 (ranging from −4.18 to 8.18).

In both of the full and subset data at FES_{25} and FES_{50}, the slopes tended to be greater than 1 and y-intercepts around 0 (Fig. 3c and 3d). One-sample t-tests showed that the slopes at FES_{25} and FES_{50} in the full data as well as at FES_{50} in the subset data were significantly greater than 1 ($P = 0.008$, $P < 0.001$, and $P < 0.001$ for FES_{25} and FES_{50} in the full data as well as at FES_{50} in the subset data respectively). Results from the one-sample t-tests also show that the intercepts at FES_{50} in the full data was significantly less than 0 ($P = 0.014$).

C. Second Method for Estimation of Contributions Using a Single Motor Point

Fig. 4 shows a summary of the average contribution and standard deviation of each motor point to the overall measured torque at FES_{25} and FES_{50} stimulation intensities using multiple linear regression. The coefficient of determination of the regression was quite high has a group median of 0.96 (ranging from 0.99 to 0.83) for FES_{25} and a group median of 0.96 (ranging from 0.98 to 0.79) for FES_{50}. A two-way ANOVA revealed a significant main effect for motor points ($P < 0.001$). No significant main effect for stimulations intensity was found ($P = 0.993$). A significant interaction was found between motor point and stimulation intensity ($P = 0.026$). Post hoc test showed no significant difference between torque contributions from motor points on the same muscle head except for VL_c and VL_d at FES_{50} ($P = 0.005$). Between torque contributions from motor points on different muscle heads at FES_{25}, VM_p was significantly different from VL_p ($P < 0.001$), RF_p ($P < 0.001$), and RF_d ($P < 0.001$) and VM_d from VL_d ($P < 0.001$) and RF_d ($P < 0.001$); at FES_{50}, both VM_p and VM_d were significantly different from VL_d ($P = 0.002$, $P = 0.004$) and RF_p ($P = 0.009$, $P = 0.010$). Overall, the trends of the torque contributions between Fig. 3a and Fig. 4 are quite similar with major significant differences between motor points on the VM and those on the VL and RF (Fig. 4).

IV. Discussion

We first demonstrated that a linear addition of twitch torque induced by a single motor point stimulus overestimated the contribution of each motor point for the computation of the knee extension torque output (Fig. 3a). We then identified the average contribution of each motor point to knee extension torque using a multiple regression analysis (Fig. 4), which represents the contribution of each motor point to knee extension torque during paired electrical stimuli.

A. Contribution of Each Motor Point to Knee Extension Torque

We confirmed the existence of three motor points for the VL muscle (VL_p, VL_c, and VL_d), two motor points in the RF muscle (RF_p and RF_d), and two motor points for the VM muscle (VM_p and VM_d), agreeing with Botter *et al.* [14] as well as Sung *et al.* [16]. Anatomically, the motor nerve of the VL branches out from the femoral nerve and divides into two sub-branches that penetrate the surface of the muscle at the proximal and distal locations, while the third location was only seen in one participant out of 22 [16]. These locations of penetration were expected to correspond to the motor points [16]. The proximal and distal motor points were confirmed using surface stimulation in all participants and the central point in 80% of participants in the study by Botter *et al.* [14]. The motor points on the RF were found at two locations [14], which corresponds to the superior sub-branch and the inferior sub-branch of RF nerve [16]. Anatomical studies showed that the VM muscle was also divided into two sub-branches: one with short, vertically-oriented fibers and the other with long, horizontally-oriented fibers [17], which agree with motor point locations on the VM muscle [14]. Thus, the seven motor points most probably correspond to major nerve branches for VL, RF, and VM.

Each motor point is expected to activate a portion of muscle fibres within a muscle. When multiple motor points are

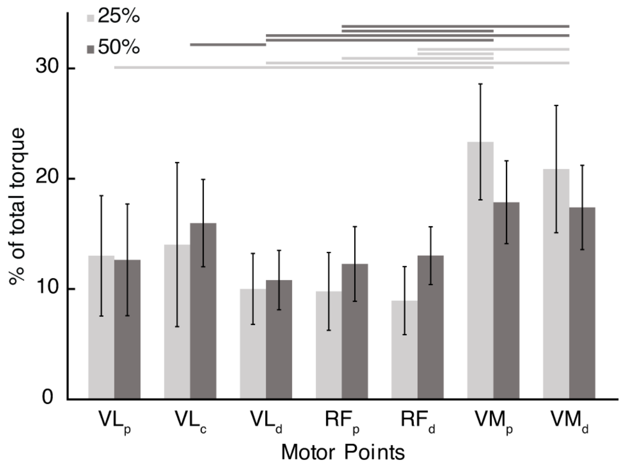

Fig. 4. Summary of the percent torque contribution of each motor point as calculated by multiple linear regression: vastus lateralis proximally (VL_p), centrally (VL_c), and distally (VL_d); rectus femoris proximally (RF_p) and distally (RF_d); as well as vastus medialis proximally (VM_p) and distally (VM_d) to the overall measured torque output at the stimulating amplitudes that produced: 25% (FES_{25}) and 50% (FES_{50}) torque of that at the maximum stimulus intensity (FES_{max}). Illustrated are the mean (SD) contributions across all participants with significance differences calculated using the Holm-Bonferroni method.

stimulated, the sum of muscle force exerted by the portions of muscle fibres generates the knee extension torque. One way to estimate the contribution of each motor point to knee joint torque is to quantify the amount of twitch torque induced by single motor points relative to the maximum twitch torque exerted by the stimulation of all seven motor points. The result of this analysis is shown in Fig. 3a. However, the sum of all contribution exceeded 100%, suggesting that each contribution overestimated the actual contribution of each motor point. Furthermore, Fig. 3b, 3c, and 3d show that the estimated torque based on these contributions were larger than the measured torque, even when we selected only motor points on the different muscle heads which were expected to include minimum overlaps. A possibility for the torque overestimation is that at larger stimulation intensities such as FES_{50}, neighboring electrodes recruit overlapping muscle fibers—meaning that in the calculation for expected torque, some of the stimulated muscle fibers would be accounted for more than once. This is supported by the significant increase in slope of the nonoverlapping subset of the data when increasing stimulation from FES_{25} to FES_{50}. Furthermore, the y-intercept of the full data becomes significantly less than 0 as stimulation intensity increases suggesting an increase in its slope which is associated with overestimation of the expected torque. These results suggest that the contribution estimated based on single motor point stimulation are not accurate and overestimate the actual contribution.

Additional recruitment of motor units does not necessarily increase muscle force linearly [18], [19]. Although an increase of M-wave monotonically increases its twitch torque contribution when the generated M-wave is small, the increase of M-wave does not increase its twitch torque contribution when the M-wave is large due to a saturation of torque contribution at higher stimulation intensities [18]. This result suggests that additional recruitments do not increase muscle force linearly, which agrees with our first result (Fig. 3).

In the second analysis using multiple linear regression, we hypothesized that linear addition of the torque contribution of each motor point generates the total knee extension torque. The results that suggest high coefficients of determinations (i.e., R^2 ranged from 0.99 to 0.79) support this hypothesis. The lack of significant stimulation intensity effect in both Fig. 3a and Fig. 4 suggests that the relative torque contribution of the motor points is independent of these stimulation intensities. This is beneficial in clinical practices as there is no need to consider the target intensity in designing the combination of motor points. The identified contribution of each motor point ranged from 9% to 23%, regardless of the stimulation intensity (Fig. 4). Specifically, motor points on larger muscle heads such as VL and VM, with reported physiological cross-sectional areas (PCSA) of $74.04 \pm 12.04\ cm^2$ and $55.40 \pm 16.12\ cm^2$ respectively [20], have correspondingly larger torque contributions compared to those that have smaller reported muscle heads such as RF, which has a PCSA of $43.06 \pm 11.88\ cm^2$ [20]. Although the individual contributions of the two VM motor points are significantly larger than those of VL, the group contribution of VL is larger than that of VM. The contributions of RF are significantly smaller than those of the VL and VM. These results represent the contribution of each motor point to the knee extension torque during paired electrical stimuli.

B. Applying the Current Results to Clinical Applications

The result of torque contribution of each motor point can be used to choose the motor points in clinical applications such as FES cycling. For example, when one has 2 channel stimulator, he/she can stimulate two motor points. To maximize the torque exertion using the 2-channel stimulator, he/she should choose two VM motor points. In the case that one has 3 channel stimulator, he/she should choose two VM motor points and VL_c. However, the contribution is based on the paired electrical stimulation and not on the tetanic stimulation (see also the following Limitation section). Also, we did not compare the current results with larger electrodes covering the entire quadriceps femoris muscles that is often used in clinical applications and that may provide larger toque output. Further investigation is required to answer this question more accurately.

We can directly and statistically compare all combinations with the same number of motor points involved. We performed the statistical comparisons for all cases, which is summarized in the supplementary result (Fig. S1-S6). While there is not an ultimate stimulation combination for a given number of stimulated motor points, there are some trends seen in combinations that result in qualitatively larger torque outputs. In line with results from the relative torque contributions, combinations that largely stimulates the VM and VL have slightly larger torque outputs than the rest while combinations that mainly stimulate the VL and RF have slightly smaller torque outputs. To more appropriately perform these statistical tests, we need to have larger sample size, as the number of cases involved in each test is too large for the relatively small sample size.

V. Limitation

Our study identified the contribution of each motor point to knee extension torque using paired electrical stimulation; however, this may not accurately represent the contribution of each motor point for NMES applications which use tetanic stimulations. As such, the results found for paired electrical stimulation should be investigated for NMES in future studies. In addition, our study used the same stimulation level in all muscles to activate the different motor points which may have distinct motor thresholds due to their unique anatomy and proximity to the surface. Of the 10 participants, 2 of them reached the max current intensity of the stimulator when evaluating their FES_{max} possibly meaning that some of the participants' true FES_{max} may be higher than what is evaluated. For our analysis on relative torque contribution, we also assume no nonlinear effects due to factors such as pennation angles as our experiments focus on the isometric condition; although we think that the effect of these factors was minimal in the current study which only uses the isometric condition and twitch contractions. Lastly, fatigue during the experiments was solely evaluated by looking at torque outputs when all motor points were stimulated at different time instances in a trial (Fig. 2c) and no fatigue was observed in this analysis; we believe that the effect of fatigue was also minimal with the relatively low stimulation intensities for the majority of evaluations (i.e., FES_{25} and FES_{50}) and rest breaks between different stimulation intensities. In the future, the contribution of each motor point during tetanic stimulation should be identified using same/similar experimental paradigms, motor thresholds should be considered when determining stimulation intensities for each motor point, stimulator units with higher current intensities should be considered to more accurately capture the participants' true FES_{max}, and other methods should be implemented to better evaluate muscle fatigue.

VI. Conclusion

We demonstrated that seven distinct motor points can be activated for the quadriceps muscle group using paired electrical stimuli and identified the contribution of each motor point to knee extension torque during the twitch muscle contraction. Clinical researchers can use these results to maximize torque by selecting motor points with the highest relative torque contributions depending on the number of available stimulator channels.

Our results do not directly indicate the same happening in NMES. However, as the paired electrical stimuli is an essence of practical NMES applications, we expect a similar contribution for each motor point during practical NMES applications, although further investigation is required. Effective stimulation is critical in maximizing the benefits during rehabilitation using NMES on quadriceps femoris muscles. The findings in the current study provides useful information to design rehabilitation using NMES on quadriceps femoris muscles.

References

[1] K. Hainaut and J. Duchateau, "Neuromuscular electrical stimulation and voluntary exercise," *Sports Med.*, vol. 14, no. 2, pp. 100–113, 1992.

[2] L. R. Sheffler and J. Chae, "Neuromuscular electrical stimulation in neurorehabilitation," *Muscle Nerve*, vol. 35, no. 5, pp. 562–590, 2007.

[3] K. Masani and M. Popovic, "Functional electrical stimulation in rehabilitation and neurorehabilitation," in *Springer Handbook of Medical Technology*. Berlin, Germany: Springer, 2011, pp. 877–896.

[4] P. H. Peckham and J. S. Knutson, "Functional electrical stimulation for neuromuscular applications," *Annu. Rev. Biomed. Eng.*, vol. 7, no. 1, pp. 327–360, Aug. 2005.

[5] M. R. Popovic, N. Kapadia, V. Zivanovic, J. C. Furlan, B. C. Craven, and C. McGillivray, "Functional electrical stimulation therapy of voluntary grasping versus only conventional rehabilitation for patients with subacute incomplete tetraplegia: A randomized clinical trial," *Neurorehabilitation Neural Repair*, vol. 25, no. 5, pp. 433–442, Jun. 2011.

[6] R. B. Stein *et al.*, "A multicenter trial of a footdrop stimulator controlled by a tilt sensor," *Neurorehabilitation Neural Repair*, vol. 20, no. 3, pp. 371–379, Sep. 2006.

[7] L. Bax, F. Staes, and A. Verhagen, "Does neuromuscular electrical stimulation strengthen the quadriceps femoris?" *Sports Med.*, vol. 35, no. 3, pp. 191–212, 2005.

[8] N. A. Maffiuletti, "Physiological and methodological considerations for the use of neuromuscular electrical stimulation," *Eur. J. Appl. Physiol.*, vol. 110, no. 2, pp. 223–234, Sep. 2010.

[9] L. D. Duffell *et al.*, "Long-term intensive electrically stimulated cycling by spinal cord-injured people: Effect on muscle properties and their relation to power output," *Muscle Nerve*, vol. 38, no. 4, pp. 1304–1311, Oct. 2008.

[10] A. Frotzler *et al.*, "High-volume FES-cycling partially reverses bone loss in people with chronic spinal cord injury," *Bone*, vol. 43, no. 1, pp. 169–176, Jul. 2008.

[11] C. Fornusek and G. M. Davis, "Cardiovascular and metabolic responses during functional electric stimulation cycling at different cadences," *Arch. Phys. Med. Rehabil.*, vol. 89, no. 4, pp. 719–725, Apr. 2008.

[12] M. Gobbo, P. Gaffurini, L. Bissolotti, F. Esposito, and C. Orizio, "Transcutaneous neuromuscular electrical stimulation: Influence of electrode positioning and stimulus amplitude settings on muscle response," *Eur. J. Appl. Physiol.*, vol. 111, no. 10, pp. 2451–2459, Oct. 2011.

[13] M. Gobbo, N. A. Maffiuletti, C. Orizio, and M. A. Minetto, "Muscle motor point identification is essential for optimizing neuromuscular electrical stimulation use," *J. NeuroEngineering Rehabil.*, vol. 11, no. 1, pp. 1–6, 2014.

[14] A. Botter, G. Oprandi, F. Lanfranco, S. Allasia, N. A. Maffiuletti, and M. A. Minetto, "Atlas of the muscle motor points for the lower limb: Implications for electrical stimulation procedures and electrode positioning," *Eur. J. Appl. Physiol.*, vol. 111, no. 10, pp. 2461–2471, Oct. 2011.

[15] D. Farina, A. Blanchietti, M. Pozzo, and R. Merletti, "M-wave properties during progressive motor unit activation by transcutaneous stimulation," *J. Appl. Physiol.*, vol. 97, no. 2, pp. 545–555, Aug. 2004.

[16] D. H. Sung, J. Y. Jung, H. D. Kim, B. J. Ha, and Y. J. Ko, "Motor branch of the rectus femoris: Anatomic location for selective motor branch block in stiff-legged gait," *Arch. Phys. Med. Rehabil.*, vol. 84, no. 7, pp. 1028–1031, 2003.

[17] L. Travnik, F. Pernus, and I. Erzen, "Histochemical and morphometric characteristics of the normal human vastus medialis longus and vastus medialis obliquus muscles," *J. Anatomy*, vol. 187, no. 2, pp. 403–411, 1995. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/7592003 and http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC1167435

[18] J. C. Dean and D. F. Collins, "Nonlinear twitch torque summation by motor units activated at M-wave and H-reflex latencies," *Muscle Nerve*, vol. 40, no. 2, pp. 221–230, Aug. 2009.

[19] E. J. Perreault, S. J. Day, M. Hulliger, C. J. Heckman, and T. G. Sandercock, "Summation of forces from multiple motor units in the cat soleus muscle," *J. Neurophysiol.*, vol. 89, no. 2, pp. 738–744, Feb. 2003.

[20] T. D. O'Brien, N. D. Reeves, V. Baltzopoulos, D. A. Jones, and C. N. Maganaris, "*In vivo* measurements of muscle specific tension in adults and children," *Experim. Physiol.*, vol. 95, no. 1, pp. 202–210, Jan. 2010.